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Comparing apples with oranges: on the functional equivalence of food products for comparative LCAs

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Abstract
Purpose In this article, we present an innovative way of deriving comparable functional systems for comparative life cycle assessments (LCAs) of food products. We define the functional unit as the contribution of one or more foods to the nutrient composition of a weekly diet and, after a product substitution, employ a product system expansion approach to search for an alternative set of products which provides an equivalent nutritional composition.
Methods Replacement is regarded within the context of a weekly diet. The comparable diet is a solution to a linear problem which finds the diet that is most similar to the starting one, subject to nutritional and/or other constraints that guarantee a minimum dietary quality. The formulation gives priority to selecting food products according to popularity.
Results We illustrate our method with two examples. We show that a baseline diet containing 3.6 servings of apples a week is equivalent to a similar diet in which the apples are replaced with 3.6 servings of oranges and servings of strawberry and kiwi are removed. These changes are necessary mainly because of differences in the vitamin C content between apples and oranges. The second example is a replacement of all meat in a weekly diet by a soy-based meat substitute. In this case, additional fish products need to be consumed to make up for a lack of selenium and essential amino acids.
Conclusions We present an innovative and objective way to overcome the challenge of comparing two or more food products in a comparative LCA. Our approach is systematic and finds the alternative diet that best meets the nutritional criteria as well as reflecting the food preferences of the population. The method selects products according to the role they play in the dietary pattern. Moreover, the method is flexible enough to allow for different selection criteria and other nutritional and non-nutritional constraints.

Keywords Comparative LCA · Food LCA · Linear programming · Optimization · System expansion · Functional unit

1 Introduction

Defining functional equivalence is a key step in any comparative life cycle assessment (LCA) study. This is particularly challenging for food products because foods differ greatly in nutritional and energy values and therefore meet different dietary needs. Moreover, the choice of a specific food product is related to many other factors partly related to properties of the food and partly related to cultural and personal preferences (e.g. taste). Even if we focus solely on the primary nutritional function (to provide energy, macro and micronutrients and water to sustain human life), functional equivalence still poses a big challenge. We present an innovative and systematic way of overcoming this by using linear optimization in a product system expansion approach.

Food LCAs have generally relied on reference flows, such as mass or volume, as functional units (Schau and Fet 2008) or servings of similar foods (Ingwersen 2012). This is clearly a drawback for comparative assertions, since no two food items are perfectly comparable from a nutritional point of view. Some other studies focus on protein content, energy or even antioxidants for comparison (Martínez-Blanco et al. 2010;

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Roy et al. 2009), but the disadvantage of these is that they pay attention to only one of the nutritional aspects.

Schau and Fet (2008) aim for a more sophisticated comparison by using a quality-corrected functional unit, while Heller and Keoleian (2012) and Smedman et al. (2010) propose a more objective aggregated score (overall nutritional quality index and nutrient density score, respectively). The last two approaches are limited by the fact that an aggregated score hides information about the specific nutrient composition of the food products. For example, two food products might be equally nutrient dense, but have a very different nutritional composition and are thus not equivalent in a diet.

In this paper, we propose an integral holistic approach where the functional unit is the contribution of one or more foods to the nutrient composition of a weekly diet. We set nutritional equivalence as a prerequisite for comparing food products and, after a product substitution, apply a system expansion approach to define changes in the amount of other food products consumed to correct for gains or losses in nutritional value to restore the balance between both diets. The two reference flows in the comparative LCA include all differences between both diets. In the LCA context, others, e.g. Saxe et al. (2012), have compared diets. However, their approach is different because they compared diets that are not nutritionally equivalent. Moreover, they analyse pre-defined diets. In our method, the shifts in products and servings that have to be added or removed to reach equivalence depend on the difference in the nutritive value of the baseline diet and the alternative diet. Consumer preference also has to be taken into account because food patterns and food habits vary within and across nations and regions and are part of the cultural heritage of countries. For example, dairy products are an important part of Dutch food culture and diet (Van Rossum et al. 2011), while rice and beans are essential in the Brazilian dietary pattern (Sichieri 2002). Our approach gives a clear insight into the likely dietary changes necessary to maintain an equal level of nutritional quality from the perspective of a total diet.

We propose here an objective method to determine which products have to be added to or subtracted from the alternative diet to provide a similar amount of nutrients as the baseline. The modified diet must be achieved by minimal changes in comparison with the baseline diet, and the selection of other products to be added or removed must be realistic, acceptable and easy to adopt by potential consumers.

To make the selection of an alternative diet, we use linear programming. Using linear programming for the composition of diets has already been exploited in the literature with different goals. Macdiarmid et al. (2012), for example, formulate an optimization problem to find a diet with minimal greenhouse gas emissions, subject to nutritional constraints. This approach, fit to the research question of their study, ignores the baseline diet and consumer preferences. In our method, the goal of the linear problem is to minimize changes to the baseline diet, subject to a set of nutritional and/or other constraints. A more comparable analysis within the nutritional literature is presented by Maillot et al. (2010). In contrast to their model, our approach uses a characteristic of the products as a weighting factor, with differentiation of decreases or increased amounts. We illustrate this with a measure of popularity, but the method is generic enough to allow for other weighting criteria.

To summarize, our method determines the nutritional properties of a baseline diet, replaces the food product or products of interest with alternatives for comparison and uses linear programming to optimize the alternative diet to obtain a similar nutritional profile as the original diet. In this paper, we describe the method for building the comparable diets, provide illustrative examples and discuss the advantages and limitations of our approach.

2 Methods

2.1 Establishing equivalent systems for comparison

The starting point is a weekly diet containing the food product or products of interest. The timeframe of 1 week is realistic from a nutritional viewpoint (Macdiarmid et al. 2012). The weekly baseline diet may be a healthy diet according to food-based dietary guidelines or an actual average diet for the population of interest.

We then compute the current value of the (selected) nutritional properties for the baseline diet and tolerance around it, for example, by increasing or decreasing the calculated amount by a fixed percentage. A similar procedure can be applied to food groups (e.g. total fruits or vegetables) and other aspects, such as price.

The calculated ranges will be used as constraints to be satisfied by the alternative diet. Careful consideration must be given to including or excluding properties and relaxing or tightening constraints. For example, nutrients considered harmful to human health, like sodium or saturated fats, do not have to satisfy a certain minimum content, but may be constrained by a maximum value. The ranges should also be checked against dietary guidelines.

The next step in the method is to replace the food product or products of interest with the one for comparison. This will be the starting point of the linear problem described in detail in the next section.

Specific food products should also be subject to constraints. In particular, the alternative food product should satisfy at least the required amount of servings. Other food items may also be constrained, for instance, to promote variety in the diet or meet certain study goals, like a vegetarian diet. Similarly, while replacing a dairy product, the proposed

alternatives should exclude any products containing dairy ingredients.

Finally, a choice must be made on how to select other products to be added or removed. Products for comparison can be selected according to specific properties, such as protein content or price. We suggest a measure of popularity to ensure a realistic alternative diet is obtained. The method can easily be extended to include multiple selection criteria, but this is outside the scope of this paper.

The diet is then optimized to find a nutritionally equivalent alternative, including the product substitution.

2.2 The linear problem

We solve the following linear problem:

$$\min_{\mathbf{x},\mathbf{u}} \begin{bmatrix} \mathbf{f}' & \mathbf{1} \end{bmatrix} * \begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix}$$

$$s.t. \begin{cases} \begin{bmatrix} A & 0 \\ \operatorname{diag}\left(-\dfrac{w_i^N}{\mathrm{den}_i}\right) & \operatorname{diag}(-1) \\ \operatorname{diag}\left(\dfrac{w_i^p}{\mathrm{den}_i}\right) & \operatorname{diag}(-1) \end{bmatrix} * \begin{bmatrix} \mathbf{x} \\ \mathbf{u} \end{bmatrix} \leq \begin{bmatrix} b \\ \left[-\dfrac{\bar{x}_i * w_i^N}{\mathrm{den}_i}\right] \\ \left[\dfrac{\bar{x}_i * w_i^p}{\mathrm{den}_i}\right] \end{bmatrix} \\ \mathbf{lb} \leq \mathbf{x} \leq \mathbf{ub} \end{cases}$$

where $\mathbf{f}'$ is an i-vector of zeros and $\mathbf{1}$ is an i-vector of ones and $\mathbf{x}$ is an i-vector with the amount of portions per week of each product i. A is a $[(2*k)\times i]$ matrix in which each row k represents a property (e.g. calories per portion, protein per portion) and each column i contains the corresponding data for a product i. Because there are lower and upper boundaries, there are two rows for each property. Accordingly, $\boldsymbol{b}$ is a $2*k$ vector in which the first k elements are the negative of the lower boundaries for each property and the last k elements are the upper boundaries. Finally, **lb** and **ub** are i vectors with the minimum and maximum amount of portions per week of each product i. We now explain the remaining terms.

In order to minimize changes to the diet, the objective function should be $\min_{xi}\sum_i |x_i - \bar{x}_i|$, where $\bar{x}_i$ represents the current consumption of product i. However, the absolute value of a difference is a non-linear function, thus not suitable for linear programming. We apply the following transformation: for each absolute difference, we add an artificial variable u_i and two constraints: $u_i \geq \bar{x}_i - x_i$ for negative deviations and $u_i \geq x_i - \bar{x}_i$ for positive deviations. In that sense, $1*u = \sum_i u_i$ can be interpreted as a penalty function which we want to minimize.

Such modelling implicitly assumes that positive and negative deviations are equally weighted. However, we want to penalize positive deviations differently from negative deviation. For example, adding a popular product should be penalized less than adding a non-popular product, while removing a popular product should be penalized more than removing a non-popular product. This split can be achieved simply by multiplying the artificial restrictions by a weighting factor which is directionally dependent: $u_i \geq (\bar{x}_i - x_i) * w_i^N$ for negative deviations and $u_i \geq (x_i - \bar{x}_i) * w_i^p$ for positive deviations.

We first normalize the weighting property as $\mathrm{norm}_{k,i} = \left(\frac{\mathrm{prop}_{k,i} - \min(\mathrm{prop}k)}{\max(\mathrm{prop}_k) - \min(\mathrm{prop}_k)}\right)$. Then we define $w_i^p = \mathrm{norm}_{k,i} + 1$ and $w_i^N = -\mathrm{norm}_{k,i} + 2$ for a property we want to minimize or $w_i^p = \mathrm{norm}_{k,i} + 2$ and $w_i^N = \mathrm{norm}_{k,i} + 1$ for a property we want to maximize.

In addition, when comparing deviations, we must decide whether to compare absolute deviations or relative deviations. This possibility is incorporated by dividing w_i^N and w_i^p by a denominator (den) which equals 1 for absolute comparisons and $\bar{x}_i$ for relative deviations. For products not consumed (i.e. $\bar{x}_i = 0$), we use the average portion size in the population of interest as the denominator. By combining and rearranging these terms, we reach the specification presented.

3 Results

We provide two examples to illustrate our method. The reference starting diet is an average weekly diet for an adult Dutch woman, calculated using data from the Dutch National Consumption Survey (RIVM 2012; Van Rossum et al. 2011). Appendix A (Electronic Supplementary Material) provides a detailed description of the baseline diet, including all products used for this analysis. Ranges for nutritional properties are calculated as a 10 % deviation from the baseline diet, corrected for the removal of the upper limits of positive nutritional properties and the lower limits of negative properties (such as cholesterol and saturated fat). See appendix B or C (Electronic Supplementary Material) for the full list of nutritional properties, including the calculated values for the baseline diet as well as the lower and upper boundaries used as constraints. Nutritional properties are calculated using the Dutch Food Composition Database NEVO 2011/3.0 (RIVM, 2011). From the Dutch National Consumption Survey (RIVM 2012; Van Rossum et al. 2011), we derive a proxy for popularity. This is operationalized as the total weight (as is) consumed from each product by the survey population. In the examples presented in this paper, we use the absolute deviation comparison. Comparative analysis of different formulations of the linear problem and/or proxies for popularity is outside the scope of this paper.

Table 1 Average milligrams of vitamin C per day in the diets under analysis

	Vitamin C (mg)
Lower boundary	84
Baseline	93
Upper boundary	102
Before optimization	123
After optimization	102

Table 3 Average nutritional values per day in the diets under analysis

	Selenium (μg)	Lysine (g)	Methionine (g)
Lower boundary	40.2	4.87	1.63
Baseline	44.7	5.41	1.82
Upper boundary	49.1	5.95	2.00
Before optimization	40.0	4.84	1.60
After optimization	41.7	4.95	1.64

We first compare apples with oranges. Our baseline diet contains 3.6 servings of apples a week. It also includes 1.2 servings of oranges, 1.2 servings of kiwis and 0.9 servings of strawberries. We replace the servings of apples with 3.6 additional servings of oranges. The immediate effect is an increased intake of vitamin C, which turns out to be the only nutritional value outside the defined boundaries (see Table 1). We use linear programming to optimize this diet. The outcome is the removal of the servings of kiwis and strawberries. Thus, the diet with 3.6 servings of apples, 1.2 servings of oranges, 1.2 servings of kiwis and 0.9 servings of strawberries is equivalent to a similar diet with 4.8 servings of oranges. Both may be regarded as equivalent functional systems, the reference flows in our comparative LCA. See appendix B (Electronic Supplementary Material) for a detailed list of all nutritional properties of the baseline diet, the diet with replacement and the optimized diet.

To see the potential consequences of such a composition of equivalent systems, we extend this example with some environmental indicators. Using data from the source document of the 'Vegetables and Fruit Calendar' (Milieucentraal, 2012), we can estimate changes in greenhouse gases (GHG) emissions, energy use and land occupation. Table 2 shows the environmental indicators per 100 g and per portion.

After computing the environmental changes, the direct substitution of the 3.6 portions of apples with oranges causes an increase of 0.12 kg CO2 eq, 1.92 MJ and 0.22 $m^2 \times$ year to the baseline diet. When corrected for nutritional equivalency, i.e. additionally removing 1.2 portions of kiwi and 0.9 portions of strawberry this difference is reduced to an increase of 0.03 kg CO2 eq, 0.97 MJ and 0.18 $m^2 \times$ year.

Our second example compares meat with a soy-based meat substitute. Our baseline diet contains 2.2 servings of chicken breast and 0.8 servings of red meat. We replace those with three servings of a vegetarian hamburger. The immediate effect is a lack of selenium and two essential amino acids, lysine and methionine (see Table 3). After limiting the increase in other meat products, the outcome of the linear optimization is an increase in the intake of fish (an additional 0.1 serving of salmon and a 0.2 serving of cod). See Appendix C (Electronic Supplementary Material) for a detailed list of all nutritional properties.

To illustrate the potential environmental impact of the exchange, we used our own data (Blonk et al. 2009; Broekema and Blonk 2009; Ponsioen et al. 2010). Table 4 shows the environmental indicators per 100 g and per portion. After computing the environmental changes the direct substitution of the three portions of meat by the meat replacer reduces the environmental impact of the weekly diet with 2.53 kg CO2 eq, 8.77 MJ and 3.34 $m^2 \times$ year. When corrected for nutritional equivalency, i.e. additionally adding fish, this difference is reduced to a lower environmental impact of 2.28 kg CO2 eq, 5.08 MJ and 3.31 $m^2 \times$ year.

4 Discussion

What are the positive and negative aspects of our approach? On the negative side, this method is computationally more intensive and requires an extensive database of nutritional and other properties for a sufficient set of food products as well as information about food preferences, and it also requires knowledge of linear programming. Both of these requirements can be met in a generic way through the use of a software package. As of now, the authors developed the software Optimeal®, which implements this method. On the positive

Table 2 Environmental indicators for products that were part of the optimization

	GHG (kg CO2 eq)		Energy use (MJ)		Land use ($m^2 \times$ year)	
	Per 100 g	Per portion	Per 100 g	Per portion	Per 100 g	Per portion
Strawberries	0.28	0.35	3.11	3.89	0.03	0.04
Orange	0.08	0.10	1.03	1.29	0.08	0.10
Apple	0.05	0.06	0.64	0.76	0.03	0.04
Kiwi	0.09	0.07	1.04	0.78	0.05	0.04

Table 4 Environmental indicators for products that were part of the optimization

	GHG (kg CO2 eq)		Energy use (MJ)		Land use (m^2 × year)	
	Per 100 g	Per portion	Per 100 g	Per portion	Per 100 g	Per portion
Cod boiled	0.91	1.09	12.92	15.50	0.00	0.00
Chicken fillet	0.51	0.38	5.40	4.05	0.74	0.56
Beef rump steak	4.64	3.48	11.78	8.83	6.63	4.98
Beef frying steak	2.95	2.22	11.70	8.77	3.02	2.26
Salmon farmed	0.33	0.40	4.93	5.92	0.29	0.34
Hamburger vegetarian	0.16	0.16	2.39	2.39	0.17	0.17

side, it is a very flexible and objective method, which provides not only a complete comparison but also one that reflects the population at hand and is therefore realistic.

Another aspect of this procedure is that it may depend on the baseline diet, since the deficiencies brought about by the substitutions will constitute the driving factors of the linear optimization. This is, in fact, an advantage, since it focuses on the nutritional or other properties to which the substituted product makes an important contribution. We advise users of our method to run sensitivity analysis with other parameterizations to check the robustness of the suggested alternative diet. As we have shown, the method also allows for simultaneous multiple substitutions to study the impact on total diets.

Since the method presented here is built on linear optimization, it suggests one (optimal) solution. As indicated in Section 2.2, the objective function can be interpreted as a penalty function. The penalty function is, in turn, a transformed summation of the number of changes needed. It is a transformed summation due to the use of (asymmetric) weights. If the weights would be symmetric and equal to 1, the penalty function would be a simple absolute summation of (portion) changes. In that sense, a higher penalty indicates more changes or a diet which is further from the starting one. In the first example (replacing apples with oranges), the penalty function values 2.3 on the solution, while on the second example, it amounts to 0.66. This reflects the fact that the first example needs more changes than the second in order to reach nutritional equivalency.

Looking at the value of the penalty function also allows for understanding alternative solutions. To illustrate this point, suppose that in our first example, it is not desirable to reduce the amount of fruit. With this additional constraint, we find a different solution. This alternative solution suggests reducing 5.7 servings of potatoes, 5.2 servings of tomatoes, 1.3 servings of juice drink and 5.5 servings of cauliflower. In this case, the penalty function is 17.99, more than 6 times higher than before. Analysing the variation of the penalty at optimal solutions with step-wise addition of product constraints gives insight over the solution space and the 'costs' of additional constraints.

5 Conclusions

In this article, we present an innovative way of deriving comparable functional systems for comparative LCAs of foods. We define the contribution of one or more foods to the nutrient composition of a weekly diet as the functional unit and search for a diet which provides an equivalent nutritional composition after replacement with the alternative in the comparison. Such a method provides an alternative diet that takes into account the preferences of the population of interest and the role of the substituted product or products in the diet.

The alternative diet is a solution to a linear problem which finds a diet that most closely resembles the baseline diet, subject to nutritional and/or other constraints that guarantee a minimum dietary quality. The formulation gives priority to the selection of food products according to a defined property, such as popularity. The method can be easily extended to allow for multiple selection criteria. With understanding of the objective function, it is also possible to test for sensitiveness and robustness of the solution. Most importantly, the method allows for a system expansion approach analysis for comparative environmental impact analysis of food products, which we believe is a step forward in food LCA.

We expect that this method can help to answer questions of the type: what is a fair comparison after a replacement of products (categories)? What is the environmental impact change once all effects are taken into account? Which foods and nutrients are critical in low-impact diets?

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References

Blonk H, Luske B, Kool A (2009) Milieueffecten van enkele populaire vissoorten. Blonk Milieu Advies, Gouda

Broekema R, Blonk H (2009) Milieukundige vergelijking van vleesvervangers. Gouda, the Netherlands: Blonk Milieu Advies,

Gouda. Retrieved from http://blonkconsultants.nl/publicaties/2009/vleesvervangers-duurzaam.html

Heller MC, Keoleian GA (2012) A novel nutrition-based functional equivalency metric for comparative life cycle assessment of food. Proceedings 8th Int. Conference on LCA in the Agri-Food Sector

Ingwersen WW (2012) Life cycle assessment of fresh pineapple from Costa Rica. J Clean Prod 35:152–163

Macdiarmid JI, Kyle J, Horgan GW, Loe J, Fyfe C, Johnstone A, McNeill G (2012) Sustainable diets for the future: can we contribute to reducing greenhouse gas emissions by eating a healthy diet? Am J Clin Nutr 96(3):632–639

Maillot M, Vieux F, Amiot MJ, Darmon N (2010) Individual diet modeling translates nutrient recommendations into realistic and individual-specific food choices. Am J Clin Nutr 91(2):421–430

Martínez-Blanco J, Antón A, Rieradevall J, Castellari M, Muñoz P (2010) Comparing nutritional value and yield as functional units in the environmental assessment of horticultural production with organic or mineral fertilization. Int J Life Cycle Assess 16(1):12–26

Milieucentraal (2012) Vegetable and fruit calendar/Groente- en fruitkalender. Retrieved from http://www.milieucentraal.nl/themas/milieubewust-eten/groente-en-fruitkalender

Ponsioen T, Broekema R, Blonk H (2010) Koeien op gras (Vol. 2010, p. 51). Gouda, the Netherlands

RIVM. (2011) NEVO-online version 2011/3.0. Retrieved January 31, 2013, from http://nevo-online.rivm.nl/

RIVM (2012) consumption_food_nut.dat Version 20111125, part of the Dutch National Food Consumption Survey 2007–2010. Bilthoven, the Netherlands

Roy P, Nei D, Orikasa T, Xu Q, Okadome H, Nakamura N, Shiina T (2009) A review of life cycle assessment (LCA) on some food products. J Food Eng 90(1):1–10

Saxe H, Larsen TM, Mogensen L (2012) The global warming potential of two healthy Nordic diets compared with the average Danish diet. Clim Chang 116(2):249–262

Schau EM, Fet AM (2008) LCA studies of food products as background for environmental product declarations. Int J Life Cycle Assess 13(3):255–264

Sichieri R (2002) Dietary patterns and their associations with obesity in the Brazilian city of Rio de Janeiro. Obes Res 10(1):42–48

Smedman A, Lindmark-Månsson H, Drewnowski A, Edman A-KM (2010) Nutrient density of beverages in relation to climate impact. Food Nutr Res 54:1–8

Van Rossum CTM, Fransen HP, Verkaik-Kloosterman J, Buurma-Rethans E, Ocké MC (2011) Dutch national food consumption survey 2007–2010. RIVM, Bilthoven